

Stability of Slope and Seepage Analysis in Earth Dam Using Numerical Finite Element Model

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Abstract

Slope stability is an important aspect of geotechnical engineering. The uses of finite element analysis of slope stability and seepage have gained popularity in recent years due to its capability to handle complex problems. Slope stability and seepage analysis of earth dam is very important to ascertain the stability of the structure. The stability of earth dam depends on its geometry, its components, materials, properties of each component and the forces to which it is subjected. The design of earth dams involves many considerations that must be examined before initiating detailed stability analyses. Such as geological and subsurface explorations, the earth and/or rock-fill materials available for construction should be carefully studied. This paper presented stability analysis carried out on Yashigou dam in China. The results of the factor of safety were considered to the Yashigou dam without water level, steady-state water level and water level drawdown by using finite element stress method analysis to compare with Morgenstern-Price method.

Keywords

Seepage; Slope Stability; Safety Factor; Geostudio Software; Yashigou Dam; Finite Element Method

Introduction

Slope stability is an important aspect of geotechnical engineering. In general, linear problems such as the prediction of settlements and deformations, the calculation of flow quantities due to steady and transient seepage are all highly amenable to solution by finite elements. The uses of finite element analysis of slope stability and seepage have gained popularity in recent years due to its capability to handle complex problems. The primary focus of this research was to study the influence of various water levels to the dam slope by using finite element analysis, and to investigate failure mechanism. Slope stability and seepage analysis using computers are easy task for engineers when the slope configuration and the soil

parameters are known. However, the selection of the slope stability method is not an easy task and the field conditions should be collected and the failure observations in order to understand the failure mechanism, which determines the slope stability method that should be used in the analysis. Therefore, the theoretical background of each slope stability method should be investigated in order to analyze the slope failure and assess the reliability of the results. Two-dimensional slope stability is one of the widely methods used in the engineer due to their simplicity. Geostudio software is one of the popular geotechnical programs based on the finite element and can consider the analysis like stress-strain, seepage, slope stability, dynamic analysis and water drawdown in the reservoir. In this research, seepage analysis in Yashigou earth dam has been done by Seep/W software in order to evaluate flow quantity, determine the phreatic surface through the cross-section of the dam. Slope/W software is used under different conditions to evaluate slope stability of the dam. Analyses for each state and each slope with Morgenstern-Price method and finite element stress method are calculated that is the minimum safety factor in each of these methods and considered as a safety factor of slope stability.

Computation Theory

Theory of Seepage for Saturated-Unsaturated Soils

Water phase and air phase of an unsaturated soil are considered as fluids, therefore problems associated with unsaturated flow are two-phase flow problem. Two partial differential equations are required to rigorously describe the flow of air and water in unsaturated soils (Fredlund, 1981). However, only flow of water is of interest in most engineering problems encountered in practice since air phase can

be assumed to be continuous and atmospheric. The air phase can be occluded when degree of saturation is relatively high, but the air pressure will essentially be atmospheric and the effect of air flow is negligible. Freeze and Cherry (1979) stated that unsaturated seepage analysis involving only the water provides results that are accurate enough for almost all practical purpose. Water flow is caused by a hydraulic head gradient. The hydraulic head (or total head) consists of the velocity head, pressure head and elevation head. The velocity head in a soil is negligible in comparison with the pressure head and elevation head, and the expression for total head can be written as follows:

$$h = \frac{u_w}{\gamma_w} + Y$$

where h = total head, u_w = pore-water pressure, γ_w = unit weight of water, and Y = elevation head above an arbitrary datum. Darcy's law can be used to describe water flow through soils in both saturated and unsaturated condition (Richards, 1931). It is stated as follows:

$$q = k_w i$$

where q = discharge per unit area, i = total head gradient, and k_w = coefficient of permeability. The general governing differential equation for two-dimensional seepage can be expressed as:

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial H}{\partial y} \right) = \frac{\partial \theta}{\partial t}$$

Finite Element Formulation for Coupled Analysis

In a coupled consolidation analysis, both equilibrium and flow equations are solved simultaneously. The finite element equilibrium equations are formulated using the principle of virtual work, which states that for a system in equilibrium, the total internal virtual work is equal to the external virtual work. In the simple case when only external point loads $\{F\}$ are applied. The finite element equation for coupled stress analysis is given by:

$$\sum [B]^T [D] [B] \{\Delta \delta\} + \sum [B]^T [D] \{m_H\} \{N\} \{\Delta u_w\} = \sum F$$

Morgenstern-Price Method

Morgenstern-Price method, one of the traditional limit equilibrium methods, has considered to be both normal and shear interslice forces, which has satisfied both force and moment equilibrium. This method satisfied all conditions of force and moment equilibrium and allowed you to specify an interslice

force function. The factor of safety obtained using a limit equilibrium method is defined as that factor by which the shear strength of the soil must be reduced in order to bring the mass of the soil into a state of limiting equilibrium along a selected slip surface. Furthermore, due to the nature of the method, the following two assumptions are made with respect to the factor safety: (a) the factor of safety of the cohesive component of strength and frictional component of strength are identical for all soils involved and (b) the factor of safety is the same for all slices.

$$F = \frac{\text{Shear strength of soil}}{\text{Shear stress required for equilibrium}}$$

Finite Element Stress Method

The finite element stress analysis of slopes concentrated mainly on deformation rather than stability analysis of slopes. In this method, no assumption needs to be made in advance about the shape or location of the failure surface. The computed factor of safety using finite element stress methods is different factor of safety as in the limit equilibrium approach. The factor of safety of a slope by the finite element stress method is defined as the ratio of the summation of the available resisting shear force, S_r , along a slip surface to the summation of the mobilized shear force S_m along a slip surface.

$$F = (\sum S_r) / (\sum S_m)$$

The available resisting force each slice is calculated by multiplying the shear strength of the soil at the base center of the slice with the base length. Therefore, from the modified form of the Mohr-Coulomb equation for an unsaturated soil the available resisting force is:

$$S_r = (c' + (\sigma_n - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b) \beta$$

Similarly, the mobilized shear force of each slice is calculated by multiplying the mobilized shear stress (τ_m) at the base center of the slice with the base length.

$$S_m = \tau_m \beta$$

Results and Discussion

Yashigou dam is combined homogeneous earth dam and located in the south-eastern of Pengyang District, Ningxia Province, China. Yashigou's latitude and longitude is $36^{\circ}05'N$ and $106^{\circ}43'E$ respectively, about 35 kilometers away from Pengyang District. This dam was built in December 1979, with the length 230 m, height 40 m, crest elevation 1627.5 m, total capacity 6,324,000 m³. In 1996, the capacity of the dam was

upgraded by increasing dam height to 43.1 m and crest elevation to 1630.6 m. In 2012, improvement in dam's storage capacity was once again provided by upgrading its height to 50.6 m and crest elevation to 1638.1 m and dam length to 267 m and to supply more

water for the irrigation. In this study, the slope stability and seepage analysis of the Yashigou dam were considered: without water level (case 1), steady-state water level (case 2) and water level drawdown (case 3) in the reservoir by using Geostudio software.

TABLE 1: GEOLOGICAL PARAMETERS OF YASHIGOU DAM

Soil Layers	Unit Weight ρ (kN/m ³)	Young's Modulus E (MPa)	Poisson's Ratio ν	Permeability k (m/days)	Void Ratio e	Cohesion c (kPa)	Friction Angle ϕ (degree)
Foundation	19.0708	14	0.334	0.01036	0.71	12	25
Region I	20.3067	7.85	0.334	0.0008398	0.57	7.6	36.8
Region II	18.816	5.89	0.334	0.01408	0.83	25.6	32.1
Region III	18.8325	4.68	0.334	0.04717	0.73	13	35.4
Silt	19.4238	8.1	0.334	0.003585	0.7	36.4	35.2
Filling	16.677	6.69	0.334	0.04724	0.81	15.9	32.4

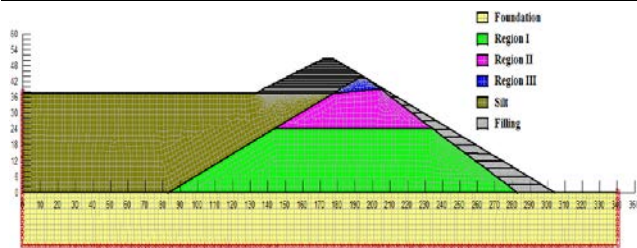


FIGURE 1: GEOMETRY AND FINITE ELEMENT MESH OF YASHIGOU DAM

Analysis of Steady Seepage

A steady analysis is to consider the situation without respect to time and the distribution of total head and pressure head are shown in Figure 2. The water table is painted as a thick blue line, which smoothly across the dam. The vertical lines are the total head isolines. They begin at 0 to intervals of 5 from downstream to upstream. The isoline of equal pressure head is 0 at water table and getting larger at intervals at 5 to the bottom until the last one that can be seen at 65. Above the water table there are isolines at negative values, which is because of the suction considered in the software by default.



FIGURE 2: PHREATIC LINE AND TOTAL HEAD AT STEADY-STATE CONDITION

Analysis of Transient Seepage

The transient analysis is actually an unsteady analysis. It can take the steady-state as the initial condition. From the transient analysis, the variation of the free

surface can be figured out, which an unsteady analysis considers several factors such as the size of the upstream shell of the dam, the fall speed of the water level, the permeability and the discharge capacity of the shell. In this study, the water level reduced to 5 meters in 4 days from the normal water level. During the process of drawdown of the water level to different elevations, unstable seepage was formed in the soil body. The pore-water pressures at different points continuously changed, and the unsaturated region continuously reflected that the location of phreatic line intermittently dropped and tended to be stable with the elongation of the time.

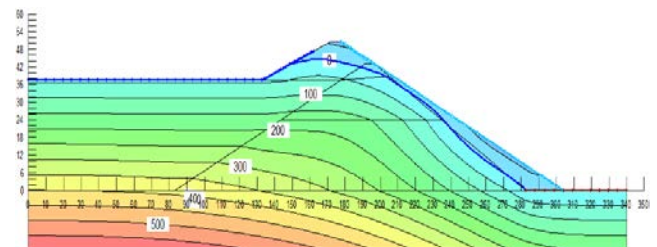


FIGURE 3: PHREATIC LINE AND PORE-WATER PRESSURE AFTER WATER LEVEL DRAWDOWN

Analysis of Slope Stability

The results indicated that it is important to use the effective shear strength characterization of the soil when performing the slope stability analysis. The computed factor of safety obtained when using a total shear strength characterization of the soil, may not agree with the factor of safety computed when using the finite element stress analysis method. The computation results disclose the law of changes in the least safety coefficient with the changes of water level and reflect the impact of different parameters and computation methods on the analysing results with the stability of slope. In the period of drawdown of

water level, the F_{smin} was not significant due to the untimely excluding of the pore-water; and the safety coefficient of the slope of the dam is minimal at the drawdown of the water level. The safety coefficient tended to become larger with the exclusion of the excess pore-water pressure with the relapse of the time. Therefore, the drawdown period is the most unsafe of all for the slope of the dam when drawdown of water level occurs to it. As a result, the safety coefficients obtained by the computation with the two methods are not significantly different from each other for all water level conditions. The factor of safety results has been computed using Morgenstern-Price method and finite element stress method as shown in Table 2 for all conditions of water level.

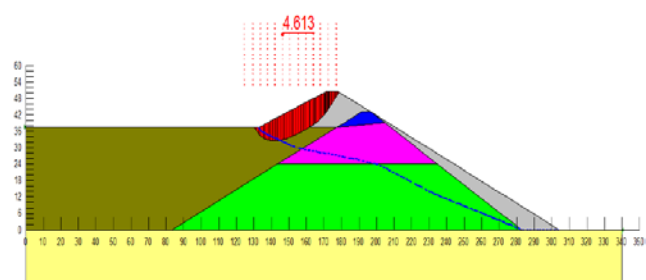


FIGURE 4: F_{smin} WITHOUT WATER LEVEL IN THE RESERVOIR BY M-P METHOD

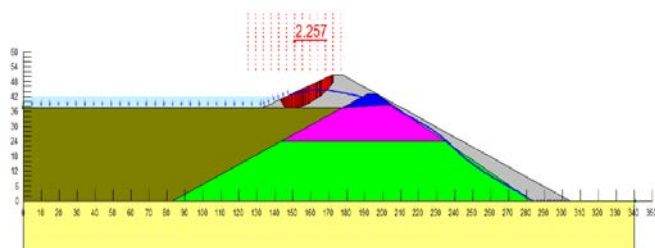


FIGURE 5: F_{smin} AFTER WATER LEVEL DRAWDOWN BY FE STRESS METHOD

TABLE 2: COMPUTATIONAL RESULTS OF F_{smin}

Analysis Method	Minimum Safety Factor		
	Case 1	Case 2	Case 3
Morgenstern-Price Method	4.613	3.511	2.495
Finite Element Stress Method	4.377	2.896	2.257

Conclusions

Based on the theory of seepage, two-dimensional seepage fields due to various conditions were established and the numerical simulation was adopted and realized by the finite element software Seep/W in this paper. The two approaches of slope stability analyses, one based on Morgenstern-Price method and the other on the finite element stress method are widely used in geotechnical engineering. Slope failure in the finite element stress method occurs "naturally" through the zones in which the shear strength of the

soil is insufficient to resist the shear stress. This method in combination with an elastic-perfectly plastic (Mohr-Coulomb) model has been shown to be suitable for slope stability analysis. In simple cases, similar factors of safety and failure mechanism have been obtained as in limit equilibrium analysis, however, under more complex conditions, the finite element stress method is more versatile because no a priori assumptions on the shape of the failure mechanism has to be made. If realistic soil compressibility data is available, the finite element solutions will give information about deformation at working stress levels. The finite element method is able to monitor progressive failure up to and include overall shear failure. So, the finite element stress method of slope stability is a more promising alternative to limit equilibrium methods and its widespread use should now be standard in geotechnical practice.

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